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Phosphate Resource Potential for Borehole Mining in the Southeastern Coastal Plain

By George H. Popper, Douglas J. Godesky, and James J. Giambra

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

g/cm^3	gram per cubic centimeter	mi	mile
ha	hectare	mt	metric ton
km	kilometer	mtph	metric ton per hour
m	meter	pct	percent

PHOSPHATE RESOURCE POTENTIAL FOR BOREHOLE MINING IN THE SOUTHEASTERN COASTAL PLAIN

By George H. Popper,[1] Douglas J. Godesky,[1] and James J. Giambra[2]

ABSTRACT

The Bureau of Mines has evaluated the extent of phosphate resources available for recovery by the experimental borehole mining method in the Southeastern Coastal Plain of the United States. Phosphate resources at overburden depths greater than 30 m are as a rule currently unsuitable for recovery through conventional mining methods because of economic, environmental, or technical considerations. In the identified deposit areas, borehole mining operations are projected to yield a more favorable rate of return and to be environmentally more desirable than conventional surface mining. Borehole mining resource estimates presented in this study are preliminary and designed to serve as a basis for future resource evaluations, as the current data base is relatively sparse and incomplete. The resulting resources have, therefore, been classified as hypothetical and speculative and are subject to updating as additional exploratory data become available.

Hypothetical and speculative resources amenable to borehole mining are estimated to total about 385 billion metric tons (mt) of phosphate matrix with a minimum in situ grade of 5 pct P_2O_5. With projected borehole mining capabilities and current conventional beneficiation procedures, this resource would make available approximately 64 billion mt of phosphate rock product at an estimated grade of 30 pct P_2O_5.

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[1]Physical scientist, former Eastern Field Operations Center, Bureau of Mines, Pittsburgh, PA (now with Office of Surface Mining, Reclamation and Enforcement, Pittsburgh, PA).

[2]Geologist (now consulting geologist, Lewiston, ME).

INTRODUCTION

This Bureau of Mines study is a preliminary evaluation of the resource potential of deep bedded, on-shore phosphate deposits projected to be suitable for borehole mining. Most of these resources are not commercially recoverable under current mining and economic conditions. However, as a result of diminution of easily mined, near-surface resources, as well as an increase in environmental constraints, a need was recognized to identify and evaluate deep-bedded phosphate deposits; these deposits may be suitable for recovery in the future using a commercial borehole mining system.

The area of study comprises the Southeastern Coastal Plain of the United States as illustrated in figure 1. The study area includes the on-shore deposits of the Atlantic and Gulf Coastal Plains. Because of the exceptionally large size of the study area, limited amount of data available on deep-bedded phosphates, and the synthesis of current authoritative interpretations of the data, the resulting tonnage estimates have been categorized as hypothetical and speculative resources. The distribution and estimated tonnages of phosphate resources should therefore be used as a basis for further refined exploration and evaluation of borehole minable deposits rather than as a conclusive and final evaluation.

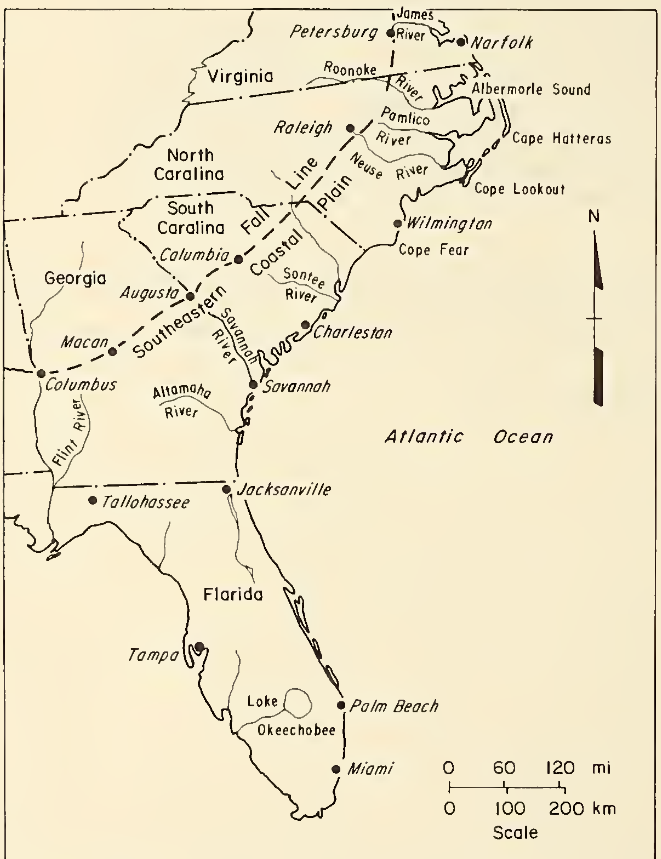

FIGURE 1. - Study Area, Southeastern Coastal Plain.

Previous investigations by the Bureau have indicated that the experimental borehole mining system should prove to be an economically and environmentally attractive method of recovering commercial quantities of phosphate under certain conditions (9).[3] The principal condition being that the phosphate deposit occurs at a depth too great to be considered economically recoverable by conventional mining and existing technology. An additional attribute of borehole mining is that it can be employed in areas where conventional surface mining would be aesthetically or otherwise objectionable.

The feasibility of the borehole mining system for recovering phosphate ore (matrix) was field tested under a Bureau contract (16). In the initial tests, about 1,500 mt of matrix was recovered at an overburden depth of 75 m. A prototype borehole mining system, designed as part of the contract, is the basis for the borehole mining parameters used in the present study. Although the prototype system has not yet been built or tested, the use of these design specifications and parameters provides a preliminary method for projecting actual mining results and resource recovery. Any interpretation of mining and resource data from this study should be utilized in this context.

Test results of a conventional beneficiation process to concentrate phosphate matrix mined by borehole methods were used to estimate the tonnage of potential

[3]Underlined numbers in parentheses refer to items in the list of references preceding the bibliography.

phosphate product. Matrix is the natural occurrence of unbeneficiated phosphate ore. It consists of the calcium phosphate mineral apatite with quartz, calcite, and dolomite; clay and iron oxide minerals comprise the gangue within the matrix (5). Washing and double-stage flotation are proposed to produce a marketable phosphate rock product.

The phosphate resource estimate presented in this report is based upon an analysis and extrapolation of public, individual, and industry data. The data base is relatively sparse and its quality variable. An extensive bibliography is included to serve as a source of current phosphate resource information for the Southeastern Coastal Plain and reflects much of the background data and research used in this study.

The location and configuration of ancient phosphate depositional environments were considered to be the primary factors controlling the distribution of existing deposits. Paleoenvironments were delineated and average deposit thicknesses, grades, and densities assigned to each area. Site-specific drill hole data were utilized but are not presented here because their inclusion would not be correlatable with the area determinations as often the drilling record was incomplete and extrapolation was necessary. Resource calculations and estimates were then made for three major areas of phosphate deposition.

ACKNOWLEDGMENTS

Grateful acknowledgement is made to the following individuals for their contributions of data and access to information, which made this study possible: J. P. Bernardi, exploration manager, International Minerals and Chemical Corp., Bartow, FL; R. C. Fountain, geological consultant, Winter Haven, FL; H. Gill and M. Hacke, U.S. Geological Survey, Doraville, GA; R. B. Hall, Gardinier Corp., Fort Meade, FL; V. J. Henry, chairman, Geology Department, Georgia State University; Atlanta, GA; P. Huddleston, geologist, Georgia Geological Survey, Atlanta, GA; J. A. Miller, U.S. Geological Survey, Atlanta, GA; S. R. Riggs, geologist, Department of Geology, East Carolina University, Greenville, NC; and T. M. Scott, geologist, Florida Bureau of Geology, Tallahassee, FL. The final opinions and conclusions expressed here, however, only represent those of the authors.

BOREHOLE MINING

BOREHOLE MINING SYSTEM

Borehole mining is an experimental method of mining that employs highly pressurized water to form an ore slurry at depth. To date, field tests have been successful and additional industry pilot-scale work is planned. Through use of this technique, phosphate matrix can be recovered from deep horizons without requiring the removal of overburden. The experimental borehole mining system, as illustrated in figure 2, may be carried out under either open- or flooded-cavity conditions. In the proposed borehole mining system, a borehole mining tool is lowered to the phosphate horizon through a predrilled steel-cased borehole. A rotating water jet on the tool disaggregates the phosphate matrix while a jet pump at the lower end of the tool pumps the resulting slurry to the surface. The slurry is then transported to a beneficiation plant by pipeline. The resulting cavity is backfilled with waste material (tailings) from the plant.

Application of the borehole mining system is not limited by matrix depth (9). Initial tests indicate that although slurry recovery rates vary, 45 mtph of matrix is a reasonable estimate of a commercially obtainable mining rate. For this evaluation, overall mining recovery is estimated to be 66 pct. These figures may vary depending upon site-specific conditions, modifications in mining techniques, or results of future tests.

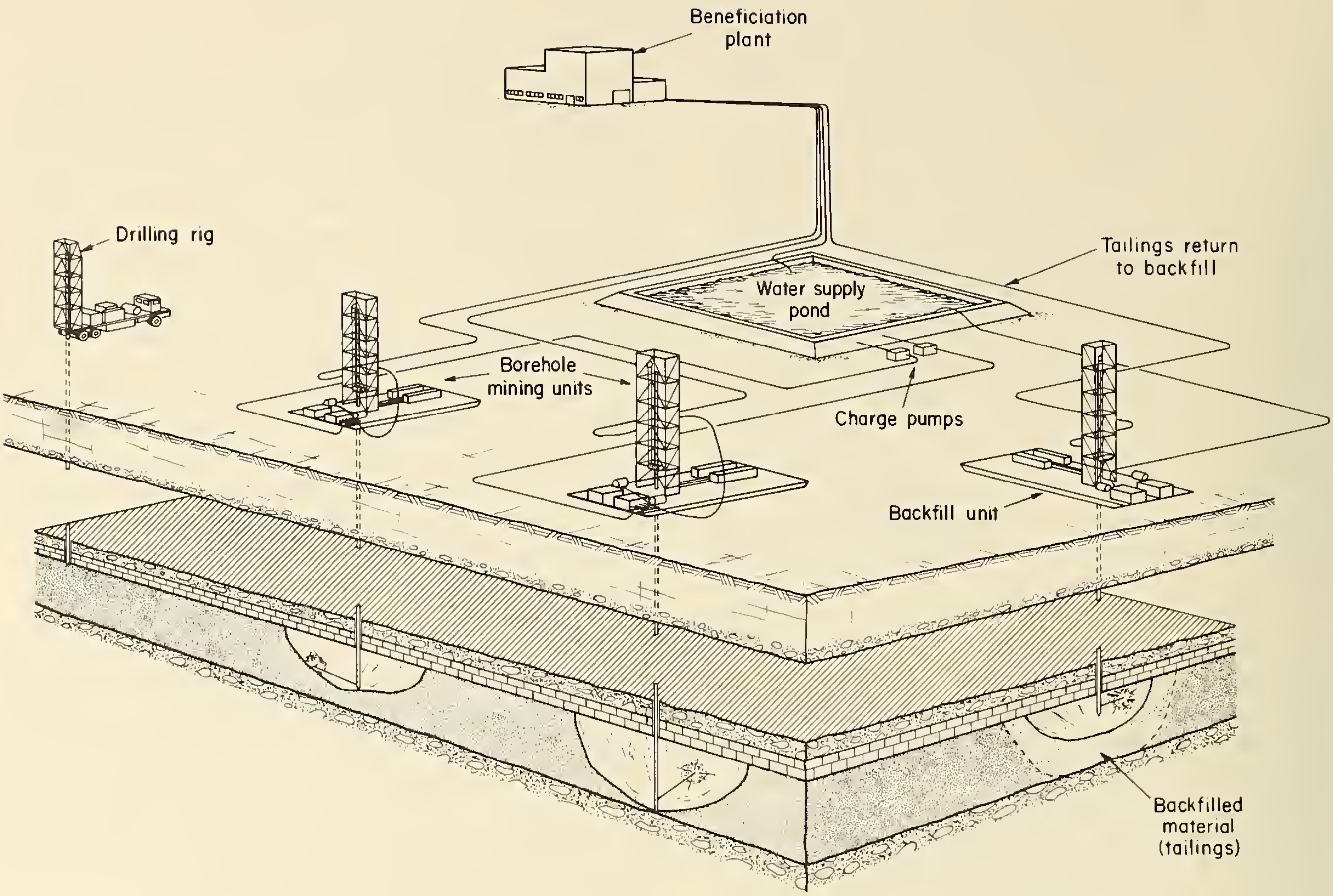

FIGURE 2. - Borehole mining system. (*Courtesy Flow Industries, Inc.*)

Drilling and mining would be conducted on a staggered grid pattern. The resulting cavities are expected to be bowl-shaped and about 18 m in diameter. A spacing of approximately 21 m between boreholes would leave a final barrier of 3 m between mined-out cavities. Anticipated borehole mining unit specifications and operating parameters are summarized in appendix A.

DEPOSITS SUITABLE FOR BOREHOLE MINING

Initial tests conducted for the Bureau indicated that relatively competent strata must immediately overlie phosphate matrix in order to carry out successful borehole mining under open-cavity conditions. This was thought necessary in order to avoid cavity collapse. Results of subsequent tests suggested that it may be possible to mine deposits where only minimal lithologic differences exist between the ore zone and the overburden provided that the operation is carried out under flooded-cavity conditions. Some contrast in lithology must exist between the matrix and the overburden in order to afford a bearing surface for the water in the cavity.

Cavity roof conditions in the resource areas identified were not determined as part of this study. Future exploration and tests may determine that some areas must be deleted from the identified resource areas if overburden conditions are such that borehole mining would not be successful. Site-specific tests will have to be made to determine each deposit's suitability for borehole mining.

Primary phosphate deposits, deposits in which no appreciable reworking or leaching have taken place, are more suitable for mining by the borehole method than those in which secondary reworking has taken place. Primary deposits tend to be consistent in thickness and uniform in the quality and distribution of the matrix; these factors facilitate exploration and make mining easier to plan.

When mining at depths shallower than 30 m, conventional mining methods are estimated to yield higher rates of return; at depths of 45 m and greater, it is anticipated that borehole mining would be the more economical method (9). In addition, the borehole technique is environmentally less disruptive at all depths. The rate-of-return threshold between conventional and borehole mining, where borehole mining is projected to yield a higher rate of return, is estimated to occur between 30 and 45 m. The present study evaluates the resource potential of phosphate deposits at overburden depths of at least 30 m. A precise deposit depth at which conventional mining systems become economically inferior or technically unfeasible has not been determined for the deposits of this large study area. A determination of that nature would vary between mining zones and conditions within the coastal plain, but will most likely occur between 30 and 45 m.

ENVIRONMENTAL CONSIDERATIONS

The borehole mining system would eliminate the need for the removal of overburden. Site cleanup, revegetation, and cavity backfilling are the only reclamation procedures required.

In using the borehole mining system, beneficiation waste is backfilled into mined-out cavities and thus long-term aboveground waste storage is avoided. Water used in borehole mining and beneficiation is recirculated within the system. Initial tests suggest also that ground water drawdown and surface subsidence would be minimal or insignificant (16). Applications of borehole mining in areas of relatively shallow overburden may have more profound environmental effects.

Borehole mining in the Southeastern Coastal Plain would be directed toward recovering phosphate from the Miocene Hawthorn and Pungo River Formations. The Hawthorn is underlain in many areas by a thick section of carbonate rocks that constitute the principal aquifer. Mining of the basal Hawthorn Formation would therefore have to be done along with monitoring of any underlying aquifer (19).

A major regional source of ground water for the study area is the Coastal Plain aquifer, formed by limestones that dip gently seaward and are covered by impermeable Miocene clays (1). Ground water is not normally free to move vertically through an aquiclude that confines a ground water system. A clay aquiclude 7 to 11 m thick underlies the Upper Miocene phosphate matrix found southeast of Savannah, GA; the clay is believed to be capable of locally protecting that aquifer from deleterious effects of mining in that region (1). Such favorable determinations would be required in other deposit areas prior to the initiation of any commercial mining operations.

Borehole mining may not be possible or desirable in areas such as barrier islands, tidal marshes, flood plains, and wildlife refuges, where environmental damage can be severe or industrial usage undesirable. In addition, urban areas, military bases, major water areas, and State and Federal forests are not considered likely mining zones because of land-use conflicts. In order to get a more reliable resource estimation, such areas were deleted from the resource calculations wherever possible. Approximately 1.9 million ha was deleted from the initial resource area. An estimate of the areas susceptible to environmental damage or land-use controversy within the identified deposit zones is given in appendix B.

GEOLOGY

GEOLOGIC HISTORY AND PHOSPHATE GENESIS

The Southeastern Coastal Plain of the United States was the site of widespread phosphate deposition during the Miocene. Phosphate was deposited discontinuously from Virginia to southern Florida on a shallow marine shelf of low relief. Resulting phosphate deposits occur in the Miocene Hawthorn, Pungo River, and correlative formations. Subsequent to deposition, there was little modification of the Miocene sequence other than minor ground water and sink hole development; structural deformation was minimal (14).

The deposition and distribution of phosphate along the Atlantic Coastal Plain was controlled by the availability of phosphate from deep ocean currents, glacially and tectonically produced fluctuations in sea level, and the paleogeomorphic setting (13, 15). Significant precipitation and accumulation of sedimentary phosphorites took place only under appropriate combinations of this complex set of tectonic and environmental variables (14).

Deposition was locally cyclic in nature and attributable to the following sequence of events. As a result of normal marine circulation, cold waters, enriched with phosphate from both organic and inorganic sources, upwelled against the eastern coastal margins. Longshore currents transported the cold phosphate-enriched waters southward along the ancient coastline. Material deposited during this time consisted primarily of terrigeneous matter with subordinate amounts of phosphate; resultant phosphate concentrations are thin and of low grade. As glaciers melted and the sea level rose, cold, deep waters transgressed local portions of the Atlantic coastal shelf. Where these currents encountered topographically raised areas, significant concentrations of phosphate were deposited in the warmer shallower waters. Phosphate accumulated in coastal basins adjacent to the ancient topographic highs. Units resulting from these conditions consist predominantly of phosphate with terrigeneous material subordinate.

As sea level continued to rise, the axis of the ancient Gulf Stream veered westward. Portions of the shelf were thus flooded with warm Gulf Stream waters. As the cold, upwelling, phosphate-producing environments were destroyed, a discontinuous carbonate caprock was deposited instead. With the onset and development of a new glacial period or tectonic event, sea level fell and erosion proceeded to remove portions or, in some cases, even the entire thickness of the previously deposited units (13).

The shape of the phosphate deposits in the Southeastern Coastal Plain is directly related to the geomorphology at the time of deposition. The troughs in which the phosphate was deposited characteristically were linear depressions or entrapment basins adjacent to associated topographic highs (14). Phosphate deposits in these zones are thin along the flanks of the arches and thicker toward the axis of the trough. The ancient topographic highs tend to be oriented either northwest or northeast and are present throughout the length of the phosphate province. The phosphate-forming environments of the Southeastern Coastal Plain are illustrated in figure 3. The structural controls are also shown. These ancient features all influenced the patterns of phosphate distribution by controlling the formation and regional accumulation of Miocene phosphorite.

LITHOLOGY

Phosphate occurs in the Southeastern Coastal Plain as phosphorite, a sedimentary rock containing at least 5 pct P_2O_5 (14). Phosphorites are composed in part of phosphate particles that may range from pebble to clay size. Generally, phosphatic particles are associated with quartz grains, carbonate grains, or clay minerals. The phosphorite may be interbedded with quartz sands, dolomite, magnesium-rich clays, or diatomite.

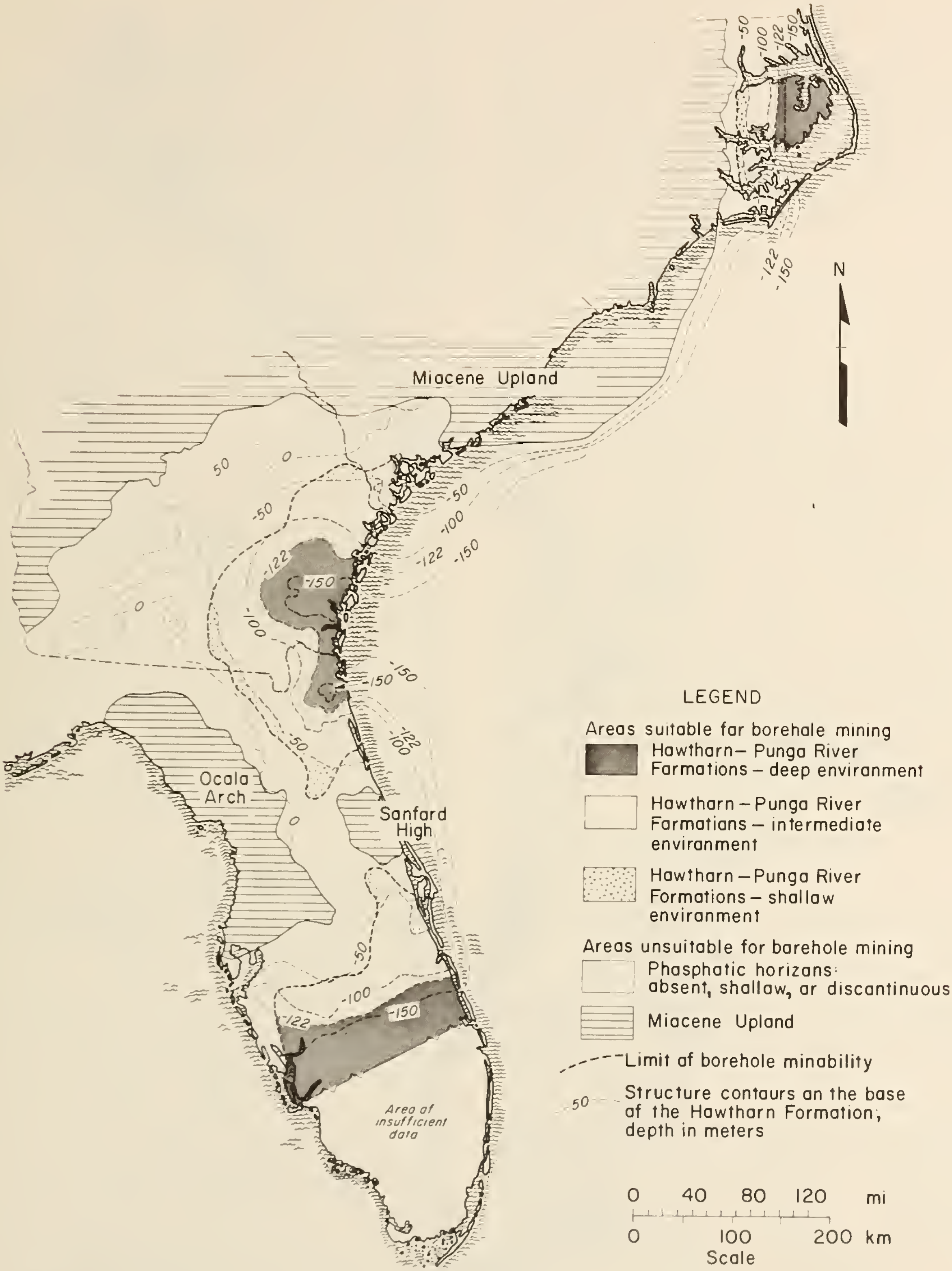

FIGURE 3. - Ancient environments of phosphate deposition (modified from references 14 and 11).

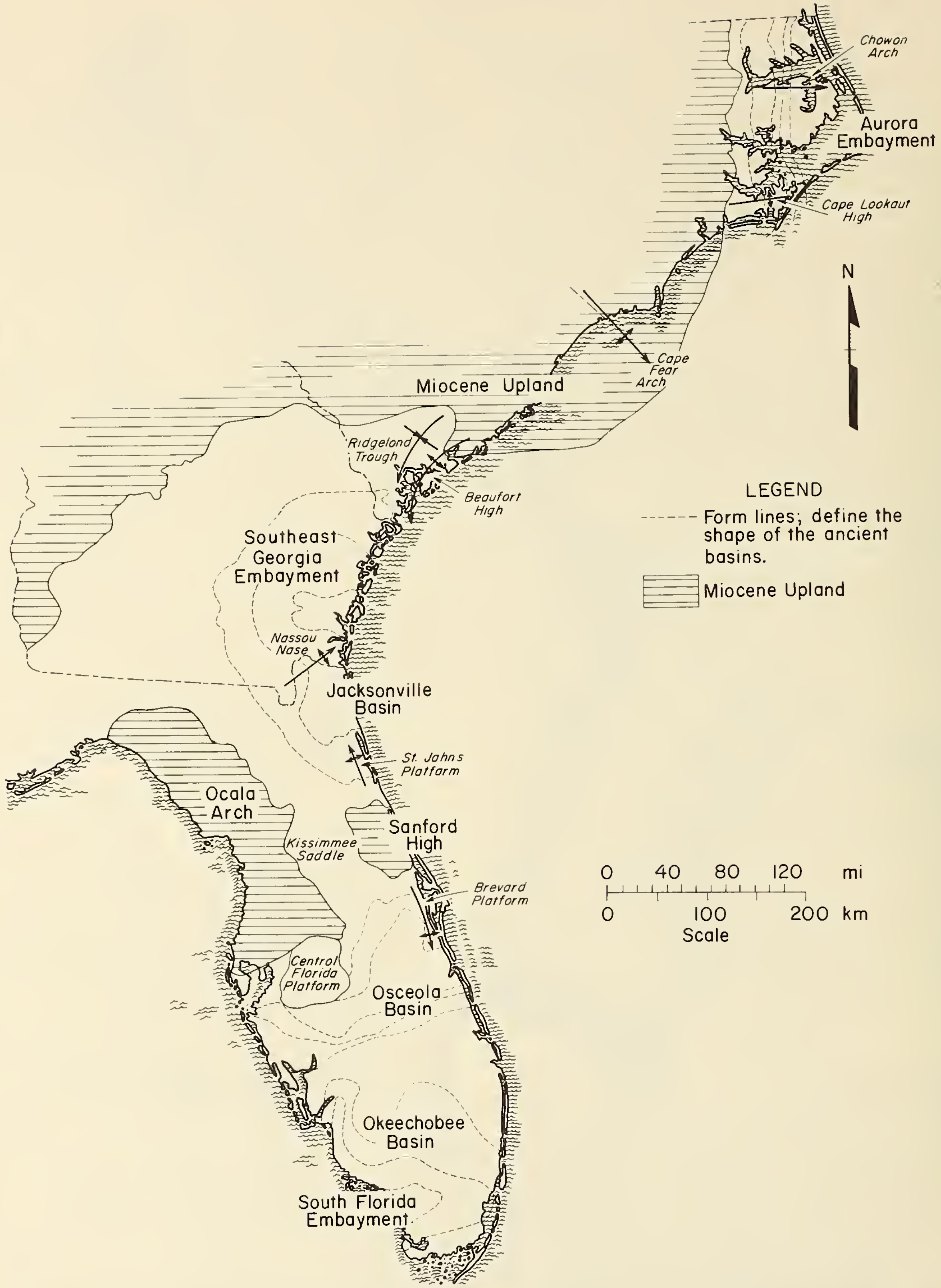

FIGURE 4. - Depositional basins of Southeastern Coastal Plain (modified from references 14 and 11).

RESOURCE DATA

AREAL EXTENT

Phosphate occurs in Miocene strata throughout the entire Southeastern Coastal Plain. Those strata having the greatest resource potential for borehole mining occur from northeastern North Carolina to southern Florida; they are termed the Pungo River Formation in North Carolina and the Hawthorn Formation in South Carolina, Georgia, and Florida.

The delineation of phosphate deposits of sufficient concentration, occurring at depths of at least 30 m, has resulted in the identification of three major depositional regions. These are illustrated in figure 4. The primary regions for borehole minable deposits are the Aurora Embayment of North Carolina, a region located eastward and downdip of the current North Carolina phosphate fields; the Southeast Georgia Embayment in Georgia plus the Jacksonville Basin and St. Johns Platform of northeastern Florida; and the Central Florida Platform, Brevard Platform, Osceola Basin, and Okeechobee Basin of southeastern and central Florida. In this report, these areas are respectively designated as eastern North Carolina, Southeast Georgia Embayment, and southern Florida.

An area of about 7.1 million ha is underlain by matrix considered suitable for borehole mining. The extent of favorable matrix within each area is presented in appendix B. Specific exploratory data that are the basis for the delineation of the deposits and region boundaries range from locally dense and reliable to sparse and interpretive. Specific drilling, mapping, geologic, and other exploratory data cannot be presented in a quantitative way in order to duplicate the resource conclusions without the qualifying interpretations by authorities on the particular data.

Within each depositional region, individual phosphate beds may not be continuous over the entire area, yet suitable matrix is assumed to exist throughout each depositional environment. Specific locations within a region may exhibit multiple beds of matrix, whereas others may contain only a single bed or no matrix. The estimated average matrix thicknesses presented are representative of total combined beds, and published regional interpretations and summary data. The matrix thickness should not be misinterpreted to indicate blanket deposition or deposits.

The potential for suitable phosphate deposits north of Albermarle Sound, NC, was discounted because of the low phosphate and high glauconite content that characterize the units of that area. Miocene strata of southwestern Georgia are probably not suitable as a potential resource because of their low phosphate content. Hard-rock phosphate deposits overlying the Ocala Arch in Florida are too shallow and discontinuous.

No determination was made for the region south of Lake Okeechobee, FL, because reliable data on phosphate bearing horizons in this area are not available. Deep-bedded phosphate is also reported to occur in small deposits outside of the identified zones, but data are sparse and the phosphorite is thought to be of limited lateral extent (7).

REGIONAL VARIABILITY

Phosphate-bearing strata exhibit a regional variability along the length of the Southeastern Coastal Plain. The Miocene section tends to thicken and deepen eastward in North Carolina, Georgia, and northern Florida; in southern Florida the section becomes thicker and deeper southward.

Generally, the percentage of carbonate units increases southward toward southern Florida where they represent the dominant lithology. By contrast, the clastic material content, mostly terrigeneous sands, increases northward and constitutes the dominant lithology in North Carolina. Carbonates, however, are also present in North Carolina where they occur principally as caprock horizons within the terrigeneous sequence.

Diatom content increases northward. Glauconite appears in the Pungo River

Formation and increases northward until it becomes a major component of strata north of Albemarle Sound, NC.

Near the ancient topographic highs or ancient shore lines, the phosphorite is characterized by erratic areal distribution and a high P_2O_5 content. In the deeper depositional environments, although the phosphorite is thicker, the P_2O_5 content of the pellets is lower, the magnesium content is greater, and the average grain size is smaller. The phosphorites in downdip areas have not been modified by supergene weathering and consequently have not been chemically upgraded (14). Dolomite content tends to increase toward the deeper portions of the depositional basins; the equivalent facies in shallow water consist of magnesium-rich clays.

Phosphate differs in character across the Southeast Georgia Embayment. Deposits of the Savannah area are similar to those of North Carolina but distinctly different from concentrations along the west and south margins of the embayment in south Georgia (6). Phosphate of the Savannah area is characterized by dark color, low pebble content, and high iron and aluminum content.

In Florida, the southern extension of the Central District contains vast reserves of relatively low P_2O_5 grade material, contained predominantly within an upper clastic section of the Hawthorn Formation (8). In addition, the MgO content is relatively high. In this area the clastic phosphorite overall grain size decreases southward as the distance from the source area increases. As with most of the resource areas, the phosphorite beds of the Hawthorn in southern Florida vary significantly in thickness and distribution, and change facies rapidly both vertically and laterally, yet the total upper clastic section has sufficient vertical and horizontal continuity to be considered a single unit (2).

OVERBURDEN

In all cases, depth to the ore zones evaluated in the present study is at least 30 m. The maximum overburden depth is over 200 m. In Florida, the Hawthorn Formation and related matrix averages over 30 m deep (4). No attempt was made to determine the viability of the overburden for cavity support as this requires site-specific evaluation. Initial testing of the borehole mining system indicated that mining must be conducted in a flooded cavity in order to avoid caving. Some contrast in lithology must exist between the ore zone and overburden in order to afford a bearing surface for the pressurized water in the cavity.

ORE ZONE THICKNESS

Borehole mining may be applied to ore zones as thin as 0.33 m; in this study, all identified matrix was at least 0.33 m thick. Phosphorite zones generally range in thickness from about 0.33 to 6 m; in some instances they are 15 m thick, rarely do they exceed 30 m (14). Representative thicknesses are given in appendix B for each depositional environment within a basin.

GRADE

A P_2O_5 content of 5 pct[4] was considered the minimum grade necessary for a phosphatic bed to be classified as a potentially minable zone of matrix. An estimated average of 10 pct P_2O_5 was used for the calculation of potential product tonnages. Matrix currently being mined in Florida has a feed grade of 10 to 15 pct P_2O_5 (20).

It is anticipated that the MgO content of the matrix recovered in much of the resource area will be higher than the levels in matrix currently being recovered in Florida and North Carolina. A high-MgO content is primarily attributable to the presence of dolomite grains in the matrix. The inclusion of MgO in phosphate flotation concentrate creates problems during the production of phosphoric acid and other products. Most of the remaining near-surface deposits in

[4]1 pct P_2O_5 × 2.184 = 1 pct BPL; BPL is bone phosphate of lime, used to express the phosphate content of matrix or beneficiated product.

central Florida contain higher than desirable levels of dolomite (17). Thus, the problems associated with high-MgO content are not limited only to borehole minable deposits.

Areas have not been eliminated from the resource estimation because of high-MgO levels, as beneficiation tests have demonstrated that it is possible to remove up to approximately 93 pct of the total MgO in matrix flotation feed (10). Other methods of reducing the MgO content such as blending and high-, low-grade zone mining can also be utilized. Site-specific beneficiation tests would have to be conducted in order to evaluate the potential amount of MgO in the product.

Generalized P_2O_5 recoveries for beneficiation of high-MgO matrix have been used to estimate potential product tonnages for such areas. Southern Florida has been evaluated as a high-MgO resource area since carbonates are the most significant and extensive contaminant of the Hawthorn phosphorites in that region (2).

Phosphate pebble is a minor constituent of Hawthorn Formation clastics, making up less than 7 pct of the total (2, 8). Deposits of low pebble content are more amenable to borehole mining and such relatively low pebble contents are characteristic of primary phosphate deposits. Alteration by leaching is not extensive in the deep bedded Hawthorn Formation and equivalent strata.

RESERVES-RESOURCES

EVALUATION METHOD

Calculation of the resource estimate was based upon two factors: the limits of the environments of phosphate deposition and the physical characteristics of the matrix in single or multiple beds (i.e., areal extent, thickness, grade, and density). Environments were delineated based upon the existing structure of the Miocene Basin. The environmental depth limits (0, 50, 122 m) are those suggested in reference 14 and are based on structure contours at the base of the phosphorite-bearing unit. The shallow environment encompasses the area between the 0- and 50-m contours. Since this study is solely an investigation of deep-bedded phosphates, only the area between 30 and 50 m was evaluated for the shallow environment. The intermediate environment extends from 50 to 122 m, and the deep environment is represented by units below 122 m. These boundaries are only an approximation of the Hawthorn bathymetry, for through time the environmental limits must have shifted markedly across the basin in response to fluctuations in sea level. An attempt has been made to account for such variations in this evaluation.

The physical characteristics associated with each environment were established based upon a synthesis of published and proprietary information, well data, drillers logs of wash borings, core descriptions, personal communications, and projections of regional trends. Extensive use was made of well logs and isopach and structure contour maps. Site- and test-specific geologic exploratory data used in this study have not been duplicated lest they be misinterpreted to indicate that the conclusions are entirely quantitative and can be substantiated without significant regional interpretation.

Hypothetical and speculative resource areas were delineated based upon the density and reliability of data and conclusions of individuals most familiar with the basins. Known variations in the physical characteristics of the phosphate zones within a specific environment were used to project the matrix characteristics into deposit areas with limited data. Average deposit thicknesses were developed for each depositional environment and then applied to the hypothetical and speculative resource areas. The final resource estimation is based upon the equation

$$r = a \times 10{,}000 \times t \times d,$$

where r = in situ resource, mt,

a = resource area, ha,

t = matrix thickness, m,

and d = density, g/cm^3

A density of 1.44 g/cm^3 was used to approximate the overall regional matrix density. The regional data used in the resource evaluations are presented in appendix B. As stated previously, within each depositional region, single or multiple phosphate beds may not be continuous over the entire area, yet sufficient vertical and horizontal matrix continuity is assumed to exist throughout each depositional environment for resource calculation requirements and recognition as a minable unit.

The regional variation in thickness of the Hawthorn Formation in North Carolina and Florida is presented in isopach maps (figs. 5-6). Isopach maps have been developed and presented with some variation by others (5). This variation can be attributed to differences in the quality and density of control data and variations in the interpretation of the Miocene section.

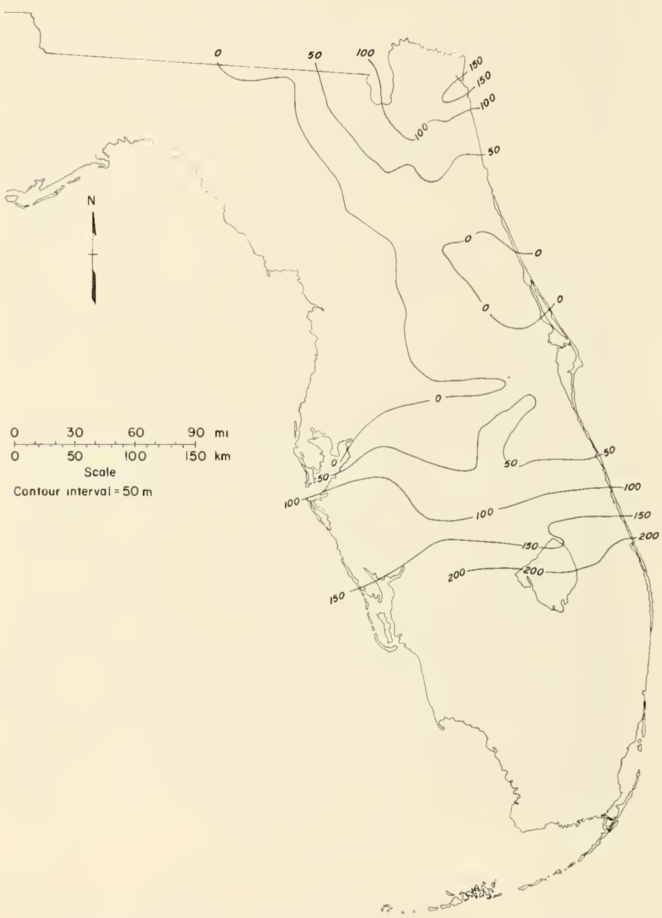

FIGURE 5. - Isopach map, Hawthorn Formation in Florida (modified from and courtesy of Florida Bureau of Geology, 1983).

RESOURCE ESTIMATE

The principles of the sedimentary phosphate resource classification system of the Bureau and the U.S. Geological Survey (18) were used in this study. According to this system, the resources identified here are classified as undiscovered, hypothetical or speculative. The classification system is presented in figure 7.

Hypothetical phosphate resources represent extensions of known phosphate bodies that may reasonably be expected to exist in the same region under analogous geologic conditions. Hypothetical resources are based upon drill hole data that have been projected for distances greater than 1.6 km.

Speculative phosphate resources occur in favorable geologic settings where phosphate discoveries have not been made

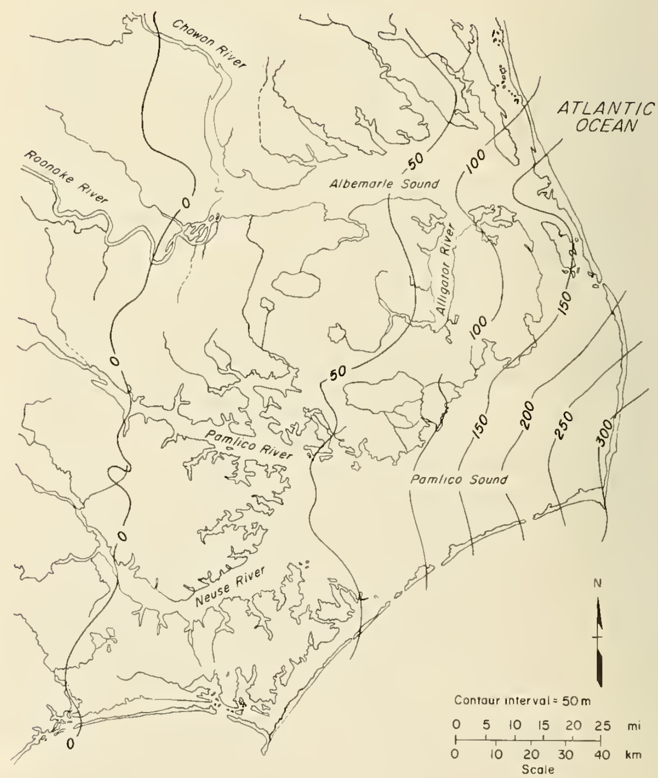

FIGURE 6. - Isopach map, Pungo River Formation in North Carolina (modified from reference 12).

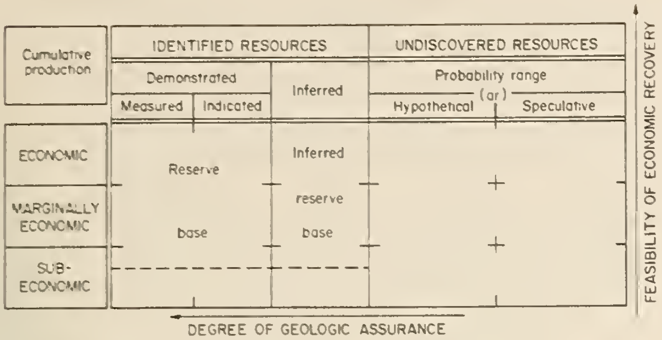

FIGURE 7. - Classification system of mineral reserves and resources.

and drill hole data are not available. If exploration reveals additional data about the quality, grade, and quantity, these hypothetical and speculative resources would be reclassified as identified resources.

It is estimated that the Southeastern Coastal Plain contains a hypothetical resource of 250.355 billion mt and a speculative resource of 135.303 billion mt of phosphate matrix projected to be suitable for recovery by a commercial borehole mining system when developed. Resource data for each depositional zone are presented in appendix B and are summarized in table 1. The borehole-mining-recoverable resources are estimated to be 165.234 and 89.300 billion mt of matrix for hypothetical and speculative classes, respectively.

POTENTIAL PHOSPHATE ROCK PRODUCT

The Bureau conducted beneficiation studies on phosphate matrix mined by the borehole technique (3). Standard double-stage flotation, the primary beneficiation method used by the phosphate industry, yielded a P_2O_5 recovery of 91.0 pct on ground ore. Standard washing with a 93-pct-P_2O_5 recovery and the 91.0-pct flotation recovery are applied here to approximate the recoverable phosphate rock product in most of the study area. For southern Florida, where matrix is anticipated to have a relatively high MgO content, results of other Bureau research were used to approximate P_2O_5 recoveries (10). For high-MgO matrix, scrubbing is anticipated to yield approximately 76 pct P_2O_5 recovery; flotation is anticipated to yield approximately a 75-pct-P_2O_5 recovery. Employing such beneficiation procedures, the borehole mining hypothetical and speculative recoverable resources would make available 43.070 billion and 21.222 billion mt of phosphate rock product, respectively, at an estimated grade of 30 pct P_2O_5. The potential phosphate rock product can be approximated by the following equation:

$$p = t \times g_1 \times r / g_2$$

where p = product, mt,

TABLE 1. - Borehole mining phosphate resource potential, Southeastern Coastal Plain, million metric tons

Primary deposit regions	In situ matrix		Recoverable matrix		30-pct-P_2O_5 rock product	
	Hypothetical	Speculative	Hypothetical	Speculative	Hypothetical	Speculative
Eastern North Carolina............	123,257	NAp	81,350	NAp	22,941	NAp
Southeast Georgia Embayment[1].........	40,346	61,776	26,628	40,772	7,509	11,498
Northeast Florida[1]...	28,687	8,309	18,933	5,484	5,339	1,546
Southern Florida[2]....	58,065	65,218	38,323	43,044	7,281	8,178
Total..........	250,355	135,303	165,234	89,300	43,070	21,222

NAp Not applicable.

[1]Northeast Florida is combined with Southeast Georgia Embayment to constitute 1 major area of deposition.

[2]High MgO beneficiation recoveries applied in southern Florida.

t = in situ matrix, mt,

g_1 = matrix grade, pct P_2O_5,

g_2 = product grade, pct P_2O_5,

and r = process P_2O_5 recovery, pct.

Beneficiation parameters are summarized in appendix A. The regional distribution for the potential phosphate rock product estimate is presented in table 1.

Another recent estimate of the hypothetical resources for the study area is about 14.275 billion mt of recoverable phosphate rock (5). This figure and others found in the literature such as an estimate of 25 billion tons, hypothetical phosphate resource in the entire United States (17), do not correspond with the estimate in this study because of differences in evaluation criteria such as maximum depth to the ore zones, deposit areas, and mining and recovery methods. Also, such resource estimates almost exclusively reflect surface minable resources. At the other end of the resource estimate spectrum, potential phosphate rock resources for the Hawthorn Formation in Florida alone have been estimated at 181 to 218 billion mt and about 45 billion mt for an area from northeast Florida through North Carolina (4).

CONCLUSIONS

The Southeastern Coastal Plain of the United States is estimated to contain a hypothetical phosphate resource of about 250 billion mt and a speculative resource of about 135 billion mt of phosphate matrix in approximately 5.2 million ha which is projected to be suitable for the application of a commercial borehole mining system when developed. With estimated mining and beneficiation recoveries, this total resource would make available approximately 64 billion mt of 30-pct-P_2O_5 phosphate rock product. This enormous on-shore phosphate reserve potential justifies continuation and expansion of exploration programs and development of a commercial borehole mining system. The application of a commercial borehole system would help to assure an adequate long-term domestic supply of phosphate with minimal effect upon other resources and the environment.

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APPENDIX A.--MINING AND BENEFICIATION PARAMETERS

BASIC DEPOSIT ASSUMPTIONS

Matrix grade, pct:	
P_2O_5	10.00
BPL	21.84

GENERAL BENEFICIATION PARAMETERS

	MgO content	
	Low	High
Recovery, pct:		
Washing-scrubbing	93.0	76.0
Flotation	91.0	75.0
Overall beneficiation	84.6	57.0
Product grade, pct:		
P_2O_5	30.00	30.00
BPL	65.52	65.52

BOREHOLE MINING UNIT-SPECIFICATIONS AND OPERATING PARAMETERS

Average unit mining rate...mtph	45
Average cavity radius...m	9.1
Cavity separation...m	3.0
Borehole separation...m	21.3
Mining recovery...pct	66

APPENDIX B.--GENERAL RESOURCE DATA

TABLE B-1. - Resource characteristics of identified zones

Region and depositional environment	Resource area, ha		Av matrix thickness, m		In situ matrix, 10^6 mt	
	Hypothetical	Speculative	Hypothetical	Speculative	Hypothetical	Speculative
Eastern North Carolina:						
Shallow	97,700	NAp	6.1	NAp	8,582	NAp
Intermediate	256,900	NAp	12.2	NAp	45,132	NAp
Deep	263,900	NAp	18.3	NAp	69,543	NAp
Total	618,500	NAp	NAp	NAp	123,257	NAp
Southeast Georgia Embayment:[1]						
Shallow	NAp	236,300	NAp	3.0	NAp	10,208
Intermediate	161,200	927,500	3.0	3.0	6,964	40,068
Deep	297,200	266,200	7.8	3.0	33,382	11,500
Total	458,400	1,430,000	NAp	NAp	40,346	61,776
Northeast Florida:[1]						
Shallow	150,600	117,100	2.4	3.6	5,205	6,070
Intermediate	506,200	21,900	2.7	7.1	19,681	2,239
Deep	125,700	NAp	2.1	NAp	3,801	NAp
Total	782,500	139,000	NAp	NAp	28,687	8,309
Southern Florida:						
Shallow	108,000	32,700	3.8	3.8	5,910	1,789
Intermediate	548,900	172,900	4.2	4.2	33,197	10,457
Deep	235,100	656,900	5.6	5.6	18,958	52,972
Total	892,000	862,900	NAp	NAp	58,065	65,218
Southeastern Coastal Plain	2,751,400	2,431,500	NAp	NAp	250,355	135,303

NAp Not applicable.

[1]Northeast Florida is combined with Southeast Georgia Embayment to constitute 1 major area of deposition.

TABLE B-2. - Extent of environmentally sensitive areas for deposit zones, hectares

Region and depositional environment	Total area	Environmentally sensitive areas				Resource area
		Coastal[1]	Water[2]	Managed land[3]	Urban[4]	
Eastern North Carolina:						
Shallow	118,500	([5])	19,500	0	1,300	97,700
Intermediate	360,400	([5])	100,200	0	3,300	256,900
Deep	332,300	([5])	63,700	2,800	1,900	263,900
Total	811,200	([5])	183,400	2,800	6,500	618,500
Southeast Georgia Embayment:[6]						
Shallow	274,000	19,900	17,800	0	0	236,300
Intermediate	1,558,700	89,200	109,800	148,300	122,700	1,088,700
Deep	819,200	161,700	74,800	15,100	4,200	563,400
Total	2,651,900	270,800	202,400	163,400	126,900	1,888,400
Northeast Florida:[6]						
Shallow	356,400	800	42,000	45,200	700	267,700
Intermediate	648,900	31,700	63,100	16,200	9,800	528,100
Deep	207,100	52,700	12,000	0	16,700	125,700
Total	1,212,400	85,200	117,100	61,400	27,200	921,500
Southern Florida:						
Shallow	194,400	([5])	40,600	0	13,100	140,700
Intermediate	994,800	([5])	237,100	8,600	27,300	721,800
Deep	1,279,000	([5])	325,900	0	61,100	892,000
Total	2,468,200	([5])	603,600	8,600	101,500	1,754,500
Southeastern Coastal Plain	7,143,700	356,000	1,106,500	236,200	262,100	5,182,900

[1]Includes barrier islands and tidal marshes.
[2]Includes flood plains, lakes, rivers, and inland marshes.
[3]Includes wildlife refuges and State and Federal forests.
[4]Incorporated limits of major cities; military bases. [5]Coastal areas excluded from initial area.
[6]Northeast Florida is combined with Southeast Georgia Embayment to comprise 1 major area of deposition; data courtesy of and modified from S. R. Riggs, Department of Geology, East Carolina University, Greenville, NC.

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